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**Characterizing the Preturbulence Environment for Sensor Development, New Hazard Algorithms
and NASA Experimental Flight Planning**

Principal Investigators:

**Michael L. Kaplan* and Yuh-Lang Lin
Department of Marine, Earth and Atmospheric Sciences
North Carolina State University
Raleigh, North Carolina 27695-8208**

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***Phone: 919-515-1442; Fax: 919-515-1463; E-mail: mlkaplan@ncsu.edu**

Table of Contents

1. Executive Summary.....	3
2. Summary of Accomplishments on Specific Research Tasks.....	4
3. References.....	8
4. Publications Resulting from the Research.....	10
5. Theses Resulting from the Research.....	11

1. Executive Summary

During the grant period, several tasks were performed in support of the NASA Turbulence Prediction and Warning Systems (TPAWS) program. The primary focus of the research was on characterizing the preturbulence environment by developing predictive tools and simulating atmospheric conditions that preceded severe turbulence. The goal of the research being to provide both dynamical understanding of conditions that preceded turbulence as well as providing predictive tools in support of operational NASA B-757 turbulence research flights. The advancements in characterizing the preturbulence environment will be applied by NASA to sensor development for predicting turbulence onboard commercial aircraft.

Numerical simulations with atmospheric models as well as multi-scale observational analyses provided insights into the environment organizing turbulence in a total of forty-eight specific case studies of severe accident producing turbulence on commercial aircraft. These accidents exclusively affected commercial aircraft. A paradigm was developed which diagnosed specific atmospheric circulation systems from the synoptic scale down to the meso- γ scale that preceded turbulence in both clear air and in proximity to convection. The emphasis was primarily on convective turbulence as that is what the TPAWS program is most focused on in terms of developing improved sensors for turbulence warning and avoidance. However, the dynamical paradigm also has applicability to clear air and mountain turbulence. This dynamical sequence of events was then employed to formulate and test new hazard prediction indices that were first tested in research simulation studies and then ultimately were further tested in support of the NASA B-757 turbulence research flights. The new hazard characterization algorithms were utilized in a Real Time Turbulence Model (RTTM) that was operationally employed to support the NASA B-757 turbulence research flights. Improvements in the RTTM were implemented in an effort to increase the accuracy of the operational characterization of the preturbulence environment. Additionally, the initial research necessary to create a statistical evaluation scheme for the characterization indices utilized in the RTTM was undertaken. Results of all components of this research were then published in NASA contractor reports and scientific journal papers.

2. Summary of Accomplishments on Specific Research Tasks

Characterization of Dynamical Processes in the Preturbulence Environment:

During the research period, work on characterizing the preturbulence environment transitioned from the 44 case study synoptic observational analyses to numerical simulation studies. The simulation studies highlighted 4 severe aviation turbulence case studies. These case studies included one commercial accident report associated with convective turbulence, one commercial accident accompanying clear air turbulence, one incident of severe convective turbulence accompanying a NASA B-757 research mission and one NASA Flight Operations Quality Assurance (FOQA) case study in severe low level convective turbulence. Numerical simulation studies with a research version of both the hydrostatic and NonHydrostatic Mesoscale Atmospheric Simulation System (MASS/NHMASS) (Kaplan et al. 2000) were performed employing horizontal grid resolutions from 30 km to as fine as 125 m in an effort to determine what dynamical processes organized the preturbulence environment. Based on these 4 case studies as well as what had been previously learned from observational analyses, it was possible to develop a dynamical paradigm of meso- α , meso- β and meso- γ scale processes that organized the preturbulence environment. The dynamical sequence of events typically started with large scale circulations accompanying 2 horizontally and vertically juxtaposed jet streak entrance regions. In this confluent region, in between the jet streaks, a very strong mesoscale front developed, as a result of the temperature and wind shear features established by the double jet streak entrance regions. These dynamical processes resulted in the concentration of rotation on a strongly sloping isentropic surface at the mesoscale. Any moist convection that developed within this favored region for turbulence was very effective at producing strong rotation downstream from the primary convective updraft. The outflow from the convective cell focused extreme rotation, vertical wind shear and buoyancy aloft near the observed turbulence typically just downstream from the convective cell's core updraft. Even in the absence of moist convection, i.e., in clear air, conditions favorable for rotation, vertical wind shear and buoyancy developed within a similar synoptic-mesoscale sequence of events. Hence, by characterizing how relatively large scale processes predispose a very fine scale region for turbulence, it then became possible to define predictive/characterization indices for eventual testing in real time predictive numerical models as well as for aiding in sensor design for onboard radars as well as other sensors. Several candidate turbulence characterization indices were developed and subsequently implemented into the operational RTTM. One of these, i.e., NCSU1 was saved from several hundred real time numerical model simulations for ultimate evaluation of its ability to characterize the preturbulence environment. Other indices, included the NCSU2 and Rienstrophy indices proved very useful in characterizing the preturbulence environment in both research as well as real time numerical simulations.

Use of Numerically-Simulated Mesoscale Fields for Initialization of the TASS LES Model:

In addition to the turbulence characterization research described in the previous task, numerical simulations of the aforementioned 4 research case studies were also employed to characterize near-turbulence scale circulations by initializing the NASA TASS Large Eddy Simulation (LES) model (e.g., Proctor 1987). Vertical soundings from these 4 case studies, generated by the MASS and NHMASS models, were employed to initialize the TASS model. The TASS model

employed grid resolutions consistent with large turbulence eddies, i.e., ~50 m or less thus producing very fine scale near turbulent motion spectra. These simulations were then compared to flight data recorder and other onboard instrumentation from the FOQA case study as well as other severe turbulence case studies, including a case study during a NASA B-757 flight, in an effort to better characterize the preturbulence environment.

Development and Testing of Indices for Turbulence Characterization in the RTTM:

The RTTM was run operationally twice daily on a computer workstation located in the Mesoscale Dynamics and Modeling Laboratory at North Carolina State University during the entire grant period. It was initialized from National Weather Service operationally available analyses, rawinsonde observations as well as surface observations with lateral boundary conditions provided from the NWS Eta forecast model fields. During this period the RTTM produced an operationally available postprocessed suite of products that included turbulence characterization indices developed from the observational and mesoscale model-based simulation experiments described in the previous paragraphs. One of these predictive indices, i.e., the NCSU1 index was archived from the RTTM for the entire grant period, i.e., from December 2001 – April 2003. This index would therefore be available for use in the verification program to be discussed later in this report.

Operational Support for NASA B-757 Turbulence Research Flights:

As noted in the previous paragraph, the RTTM was running twice daily during the entire grant period at North Carolina State University. The postprocessor was modified to produce a suite of products that NASA-Langley forecasters could utilize for, primarily, but not exclusively, convective turbulence forecasting which were available at: <http://shear.meas.ncsu.edu/>. This included the new turbulence characterization indices, described above, as well as other turbulence characterization parameters, including specific convective forecasting parameters and several thousand atmospheric soundings and sounding parameters. These convective forecasting parameters would allow the NASA forecasters to determine, several hours in advance, whether or not convection was likely to occur in a specific location, its intensity and timing. Thus, forecasters could plan B-757 missions with a sense of expectation of when and where convection would occur, its intensity, as well as the likelihood or not that turbulence would accompany the convection as well as the anticipated intensity of the turbulence. The turbulence characterization capabilities of the RTTM products could provide additional valuable information for NASA forecasters thus allowing the research aircraft to move to the region where turbulence was most likely to occur and then to collect turbulence data for use in potential sensor design. Also, this enabled the testing of the utility of new turbulence characterization indices under realistic atmospheric conditions.

Improvement of the RTTM's Prediction of Convection:

One of the consequences of utilizing a numerical simulation model to characterize the preturbulence environment is the accumulation of understanding of model systematic biases and errors. These biases are most important concerning the model's ability to predict convection since convective turbulence is the primary focus of NASA-Langley's TPAWS program. Without

an accurate simulation of convection it is extremely difficult to assess the utility of predictive indices designed to characterize the preturbulence environment since the indices indicate how convection interacts with the background flow to create an environment favorable for turbulence. The RTTM employs the Kain-Fritsch (e.g., 1992, 1993, 1998, 2004) convective parameterization scheme within the MASS numerical model (e.g., Kaplan et al. 2000). Based upon numerous weeks of RTTM simulations during the spring and summer months, it became apparent that the model systematically overpredicted the distribution of convective precipitation on days when the surface temperatures were high, relative humidity low and large scale upward vertical motion fairly weak. This problem resulted in the triggering of turbulence characterization index values in regions where convection did not exist in nature. A concerted effort was therefore required to minimize this problem in order to enhance the reliability of RTTM turbulence potential forecasts. In an effort to solve this problem, numerous tests were run with a research version of the RTTM. Parameters in the Kain-Fritsch convective parameterization were tested for their sensitivity to this problem. Specific case studies were tested but results were mixed. A research version of the RTTM with the Grell (1993) scheme was also tested, further resulting in mixed results. Then access to a new version of the Kain-Fritsch convective parameterization scheme, which Dr. John Kain of the National Severe Storms Laboratory had developed specifically to rectify this problem, became possible. This version of the scheme was acquired from Dr. Kain and transferred to the research version of the RTTM for testing and preliminary results indicated improvement, i.e., less overprediction of convective precipitation on days with strong surface heating but weaker large scale forcing. Statistical validation procedures were developed and employed to test the improvement on four case studies from the summer of 2002.

Development of a Turbulence Index Validation Scheme for the RTTM:

In order to demonstrate the utility of the RTTM and its turbulence characterization indices, it would be necessary to design a unique statistical validation capability that employed commercial aircraft observations of turbulence location and intensity. This is so because turbulence is reported with widely varying pilot reports from primarily commercial aircraft, i.e., PIREPS. These reports are essentially the only source of observed data against which RTTM indices can be compared on a daily basis for numerous case studies. Validating the RTTM can tell us whether or not our indices are properly characterizing the preturbulence environment. If we show reasonable skill then we can have some confidence that our theoretical paradigm of turbulence generation processes is accurate, as our indices are based on that paradigm. In order to do this, we plan on employing a validation scheme which we were developing for validating convective precipitation in the RTTM. Both convection and turbulence are fine scale and transient. These phenomena are sensitive to very fine scale measures of atmospheric forcing as distinguished from the broad scale atmospheric phenomena that create a favorable environment for convection and turbulence. Hence, the statistics must be sensitive to transient and very fine scale events. The statistical procedure, that we are in the process of testing, involves employing the Critical Success Index (CSI), Total Skill Score (TSS), and Heidke Skill Score (HSS). These statistics will be calculated based on various thresholds of the NCSU1 index for different classes of turbulence severity (e.g., Koch 1985; Doswell et al. 1990; Lee and Passner 1993; Manobianco and Nutter 1998; White et al. 1998). This validation technique is directly comparable to what we have developed for validating the new convective parameterization scheme in the RTTM. It considers false alarms, hits, misses and nonevents. Work is preceding forward on this validation

in which NASA-Langley will be supplying us with nearly two years of PIREP data for comparison to the RTTM NCSU1 index calculations during the grant period and beyond.

Publishing the Results of the Research

In an effort to publish the results of the research, 2 different types of publications were generated. First, 3 NASA contractor reports were generated, i.e., Kaplan et al. (2002, 2003, 2004). Second, 3 refereed scientific journal publications were generated, i.e., Kaplan et al. (2004a,b,c). The publications dealt with 3 fundamental aspects of the research: 1) the 44 case study synoptic observational analysis and its implications for the preturbulence environment, 2) the multi-scale paradigm organizing severe turbulence based on mesoscale numerical model simulations of the preturbulence environment and 3) the RTTM and its ability to simulate the preturbulence environment as well as the utility of preturbulence environment indices.

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